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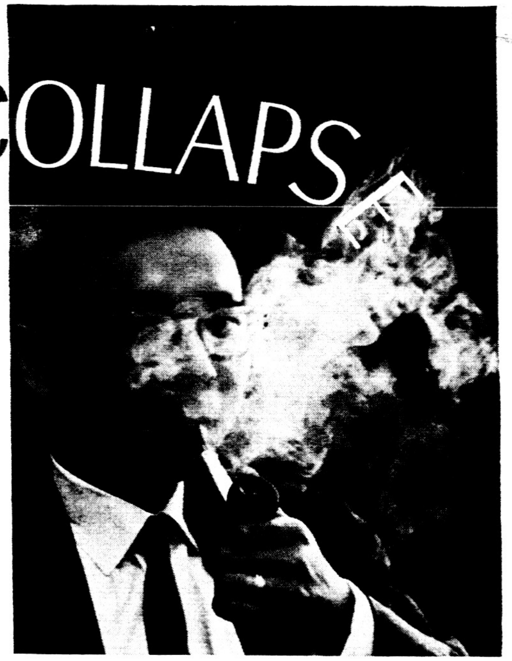
GRAVITATIONAL COLLAPSE



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Quasi-stellar radio sources, a subject of intense interest since their discovery in 1960, were the central theme of the International Symposium on Gravitational Collapse and Other Topics in Relativistic Astrophysics, held in Dallas, December 16 to 18, 1963. During the meeting, at the request of L. V. Berkner, it was renamed the John F. Kennedy Memorial Symposium. The author of this review of the discussions is a physicist at NASA's Goddard Institute for Space Studies and an adjunct assistant professor at Columbia University.

By Hong-Yee Chiu

With the exception of a few supernova remnants which are in our galaxy, most cosmic radio sources are "radio galaxies". Although flare stars do emit radio waves occasionally, no ordinary stars with strong, steady radio emission have been found. The typical optical power of stars is from 10^{30} ergs/sec (white dwarfs) to 10^{38} ergs/sec (super giants). For comparison, the optical power of the sun is 4×10^{33} ergs/sec. The typical radio power of supernova remnants is around 10^{36} ergs/sec. For a giant galaxy (containing approximately 10^{11}–10^{12} stars with a total mass of around $10^{11}\odot$, where $\odot$ = solar mass = 2×10^{33}g), the optical power is around 10^{44} ergs/sec. Radio emission from normal galaxies is generally weaker, the power ranging from 10^{37}–10^{39} ergs/sec. For certain peculiar galaxies, the so-called "radio galaxies," the radio emission rate ranges from 10^{41}–$10^{44.5}$ ergs/sec.

However, since 1960, another kind of strange object has been found—"quasi-stellar radio sources"; these formed the center of discussion at the symposium. Their radio power is around 10^{44} ergs/sec and their optical power is around 10^{46} ergs/sec, *which is 100 times the total energy output rate of a giant galaxy!* To date nine of these objects have been found. On photographic plates, these peculiar radio sources have star-like appearances, and one of them showed erratic light variations with a time constant of the order of one year and a long-term quasi-period of ten years. A modest estimate of the total energy content of each of these objects (in the form of the kinetic energy of electrons of 1 BeV energy) gives a minimum of 10^{60} ergs, which is the *rest energy* of about 10^{6} suns.

Are "quasi-stellar radio sources" stars? Ordinary stellar-structure theory precludes stars of mass greater than $100\odot$. In such stars, radiation pressure dominates and because of the thermodynamic properties of radiation, these stars will pulsate with large amplitudes. As a result of this pulsation, mass will be ejected, thereby reducing the mass of the star. Are "quasi-stellar radio sources" galaxies? Their angular size is less than 0.5″, while normal galaxies at corresponding distances (determined by their red shift) will have an angular size of the order of 3″. In several cases, the light variation precludes this possibility because galaxies do not have light variations.

So far, the clumsily long name "quasi-stellar radio sources" is used to describe these objects. Because the nature of these objects is entirely unknown, it is hard to prepare a short, appropriate nomenclature for them so that their essential properties are obvious from their name. For convenience, the abbreviated form *"quasar"* will be used throughout this paper.

The idea of having a meeting on gravitational collapse came after the discoveries of the enormous energy output of quasars and the subsequent gravitational-collapse theory of F. Hoyle of Cambridge University and W. A. Fowler of the California Institute of Technology to explain this enormous energy output. When the symposium met, the original hypothesis of Hoyle and Fowler (reviewed at the meeting by E. M. Burbidge of the University of California at La Jolla) was abandoned and was replaced by those to be reported

Acknowledgement: The author wishes to thank T. A. Matthews, A. R. Sandage, C. Hazard, M. B. Mackey, A. J. Shimmins, H. J. Smith, D. Hoffleit, W. Priester, and Miss Jane Woodbridge for their help in preparing this report. Thanks are also due to the editors of the *Astrophysical Journal, Sky and Telescope,* and *Nature* for permission to use a number of previously published illustrations.

Some 300 astronomers and astrophysicists attended the symposium, among them (left to right) André Mercier, Fred Hoyle, Margaret Burbidge, Alfred Schild, Ray Littleton, and Vaclav Hlavaty. The meeting was sponsored by the Southwest Center for Advanced Studies, the University of Texas, and Yeshiva University, with the support of the Aerospace Research Laboratories, Wright-Patterson Air Force Base, the Air Force Office of Scientific Research, the National Aeronautics and Space Administration, the National Science Foundation, and the Office of Naval Research.

later. Meanwhile, new observational data had been accumulated and were presented at the meeting. It seems safe to say that, at the present time, the interior structure and the physical mechanism of the energy production of quasars are still not understood.

Fusion of hydrogen into heavier elements will yield an energy of about one percent of the rest energy of matter. If the energy source of the quasars were nuclear in nature, it would be necessary that $10^8 \odot$ of hydrogen be burned in around 10^6 years. It is rather unlikely that nuclear energy could be released in unison on such a large scale. Moreover, nuclear reactions usually take place in the interior of a star; the energy released gradually diffuses out, and finally is radiated thermally as black-body radiation, peaked at an energy of around 2 eV. How can the energy of electrons be elevated from a few eV to a few BeV without violating the second law of thermodynamics? Using the most efficient thermodynamic cycle, a nuclear-energy source many orders of magnitude higher is needed! Therefore, there is only one energy source left for us to consider: gravitational energy. Incidentally, the gravitational field is the weakest field in nature, but it is the only one that allows us (at least theoretically) to extract up to 8/9 of the rest energy of matter.

After this brief introduction to the central theme of the discussions, I shall now report the individual papers that were presented at the symposium. In order to have continuity in this report, I shall not report the talks chronologically, but in a logical manner.

Reviewing the common properties of radio sources, T. Matthews of Caltech pointed out that radio emission from normal galaxies is rather weak compared with their optical emission. Their radio power is around 10^{37-39} ergs/sec while their optical power is around 10^{44} ergs/sec. Some rare, peculiar spiral galaxies may have a radio emissive power of around 10^{40} ergs/sec. Strong radio galaxies with a radio power of 10^{41-44} ergs/sec are most frequently found among the so-called D systems. These are galaxies with excessively bright nuclei (Seyfert galaxies). Some strong sources are also identified with elliptical galaxies. The optical emission rate of quasars is around 10^{46} ergs/sec and their radio emission rate is around 10^{44} ergs/sec. (See Fig. 1 for a plot of radio and photographic magnitudes of galaxies and quasars.)

To date, a total number of nine quasars have been identified from the contents of the revised 3C catalogue (3C stands for the *Third Cambridge Catalogue of Radio Sources*) which contains about 470 radio sources, many of them still unidentified optically. This catalogue was compiled by a group working under M. Ryle of the University of Cambridge. The two quasars which have been extensively studied and which were extensively discussed at the meeting have catalogue numbers 3C273 and 3C48 respectively.

Radio interferometers with a resolution of the order of 1″ of arc were first used to study the shape of some of the stronger quasars. This method also enables one to locate accurate positions for these sources. This was done chiefly by the Manchester group (R. P. Allen, B. Anderson, R. G. Conway, H. P. Palmer, V. C. Reddish, and B. Rowson) and by the Caltech group (P. Maltby, T. A. Matthews, and A. T. Moffet). In the radio position of 3C48, an object resembling a 16^m star was found on the photographic plates.* This "star" was surrounded by a nebula measuring 5″ × 12″ which does not resemble any galaxy. (See Fig. 2.)

At the same time, lunar occultation observations of 3C273 were carried out by the Australian group (C. Hazard, M. B. Mackey, and A. J. Shimmins). This other method of observation provided an

* Superscript *m* stands for the magnitude; $m = -2.5 \log_{10} F + C$ where F is the observed energy flux and C is a constant. At a distance of 32.5 light years the sun has a magnitude of +4.85. This is also the distance at which the absolute magnitude of an object is defined. A 6^m star is just barely visible to the eye. A difference of 5 magnitudes amounts to a difference in measured energy flux of 100.

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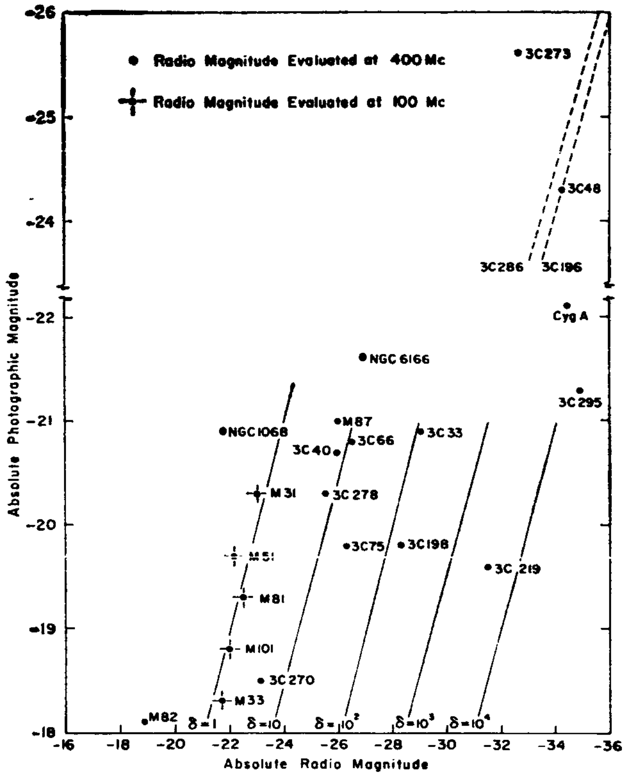
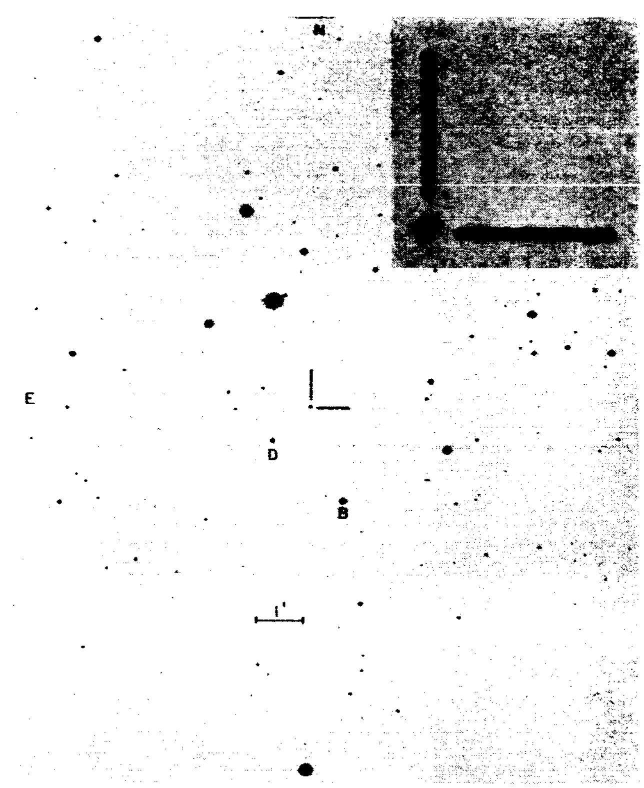
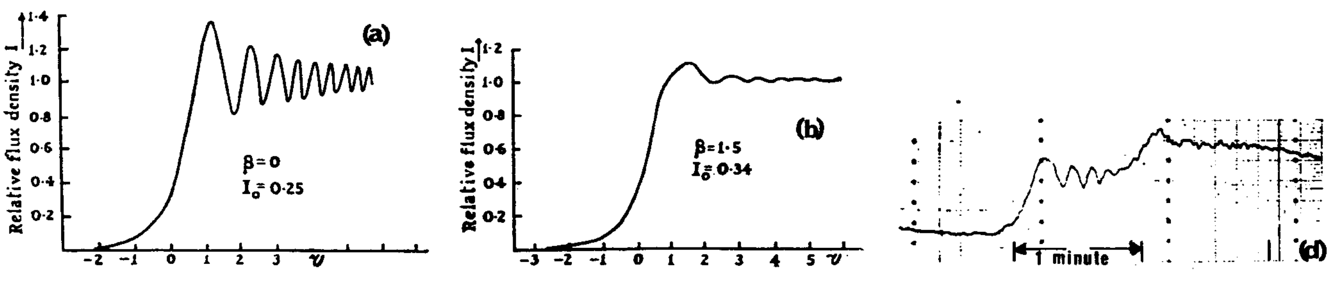


Fig. 1: Above, a plot of absolute radio magnitudes and absolute photographic magnitudes of galaxies and quasars. The absolute photographic magnitude, a measure of the optical power, is defined in the footnote on p. 22. The absolute radio magnitude M_r is defined to be $M_r = -54.1-2.5 \log_{10}S$ where S is the radio power in watts per second per cycle bandwidth at 400 Mc/sec, with the exception of a few normal galaxies where S is evaluated at 100 Mc/sec; δ is the ratio of radio power to optical power normalized to unity for normal galaxies. Other radio galaxies have a value of δ up to 10^4. Quasars 3C273 and 3C48 are found in a region in the graph where no galaxies are found. The distance of two other quasars (3C286 and 3C196) have not been determined and their possible position in this graph are indicated by the dotted lines. The sources of data used here are references 1 and 2.

Fig. 2. Below, an actual photograph of 3C48 (shown in enlarged image at upper right). Objects D and B are reference stars from which the magnitude of 3C48 is determined. A faint nebulosity can vaguely be seen. (Photo by T. A. Matthews and A. R. Sandage taken with Hale Telescope, Mt. Palomar, Ref. 3).





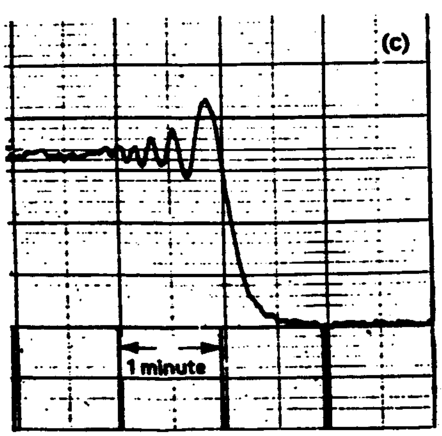


Fig. 3. Intensity observed as function of time in lunar occultation: (a) shows diffraction pattern calculated for a point source; (b) shows that of an extended object. Note decrease in amplitude for an extended object. Angular diameter ω is related to β by $\omega = \beta/(\lambda/2d)^{1/2}$ where λ is the wave length and d the distance to the moon; v is proportional to the time; v = 0 corresponds to the geometrical shadow; I_0 is the relative flux density at the edge of the geometrical shadow. An actual emersion diffraction pattern of 3C273 at 410 Mc/sec on August 5, 1962, is shown in (c). Note the similarity to that for a point source (a). Immersion diffraction pattern of October 26, 1962, at 1420 Mc/sec, is shown in (d). Note resolution of 3C273 into point source and extended source (Ref. 6, 7).

optical identification for 3C273. Because of gravitational perturbations, the orbital plane of the moon is not fixed in space but precesses with a period of around 19 years. Thus, the moon, with an angular size of 30 minutes of arc, can occult stars within a belt of 20° as it moves around the earth. When a radio source is occulted, one can learn from the diffraction pattern about the location, shape, and size of the radio source. Fig. 3 shows some observed diffraction patterns of 3C273. In particular, it is easy to tell if a source is an extended one. It was found that 3C273 consists of two sources, *A* and *B;* their separation is 19.5″ (see Fig. 4). Component *B* is slightly elliptical and four times weaker than component *A*. Using the 200″ Hale telescope, A. Sandage of Mt. Wilson and Palomar Observatory obtained photographs which show, at the radio position of *A,* a nebula shaped as a jet, pointing away from a 13^{m} star-like object which is identified as component *B*. One of Sandage's photographs appears in Fig. 5.

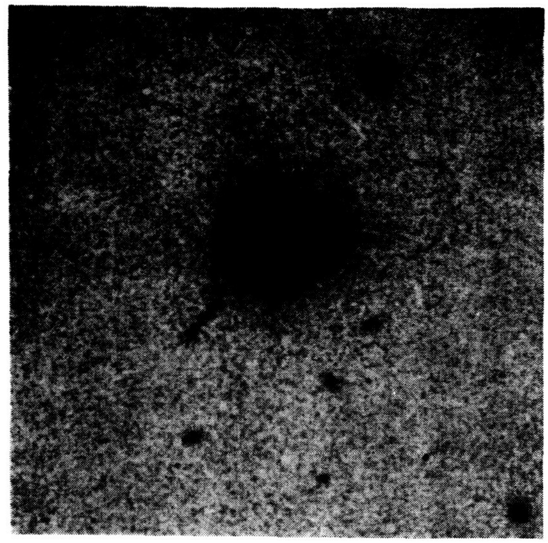


Fig. 5. Photograph of 3C273. Note the jet which points away from the starlike object. Although its distance is 1.8×10^{9} light years, this object is easily seen through an amateur's 6″ telescope. (Photo by A. R. Sandage with Hale telescope at Mt. Palomar.)

Radio spectra for both components of 3C273 and for 3C48 have been obtained. Briefly, the mechanism for radio emission and the nature of radio spectra can be described in the following way. The optical radiation of stars and nebulae is chiefly emitted by thermally excited ions. The spectra of stars and nebulae are rich in absorption or emission lines; their over-all features can be understood in terms of black-body radiation peaked around certain optical wavelengths. The radio spectra that are normally observed can be broadly classified into two categories: thermal and synchrotron emission. In the thermal spectrum, the intensity per unit frequency increases towards shorter wavelengths for emission from "optically thick" emitters. This kind of spectrum resembles that of the long-wavelength end of a black-body thermal radiation, hence its name. Most likely it is produced by electron bremsstrahlung, which occurs when electrons pass very near ions. In the synchrotron spectrum, the intensity decreases towards the shorter wavelengths, and usually the intensity per unit frequency is proportional to $\nu^{-\alpha}$, where ν is the frequency and α is a positive number usually between 0.3 and 1.2 (for most sources, α has a value of around 0.8).

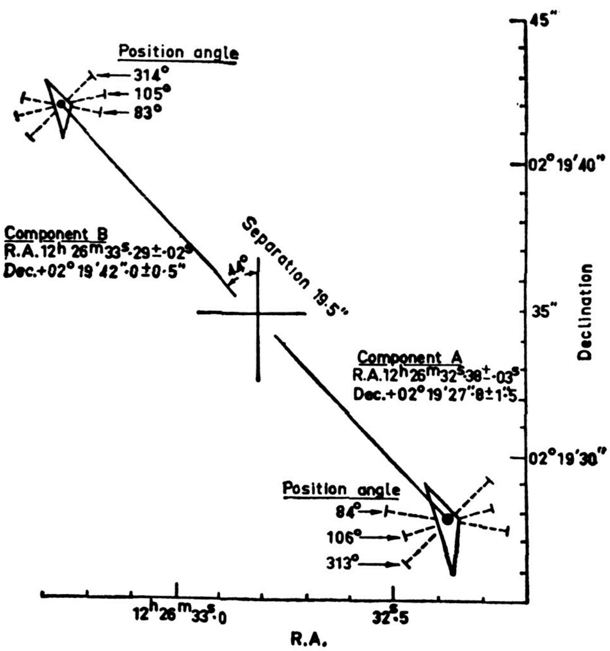


Fig. 4. Diagram of the radio source 3C273. Sides of full triangles represent position of limit of moon at time of occultation. Broken lines represent widths of equivalent strip source as measured at 410 Mc/sec for each of three position angles indicated. (Ref. 6).

The paths of electrons in a magnetic field are not straight lines but curves. Hence these electrons suffer acceleration while traveling on a curved path. These "accelerated" electrons then radiate polarized electromagnetic waves, primarily in the radio region. Such radiation from monoenergetic electrons was first observed in electron synchrotrons, hence the name synchrotron radiation. The observed cosmic-ray spectrum is usually

$$N(E)dE = E^{-k}dE$$

where $N(E)dE$ is the flux in the energy band dE and k is a positive number; $k = 1.5$ for high-energy cosmic-ray particles. We may assume that the relativistic electron component of cosmic rays also obeys this law. Then the synchrotron radiation intensity per unit frequency is proportional to $\nu^{-\alpha}$.

The radio spectrum of 3C273 shown in Fig. 6 is a composite of the two sources *A* and *B*, and can be resolved as indicated. This resolution was obtained from lunar occultation observations. The spectrum of *A* seems to belong to the synchrotron type, and that of *B* to the thermal type. However, this interpretation of the observed spectrum of source *B* would require a temperature of the order of 10^9 °K. Such a high temperature contradicts the lifetime estimated by present theory.

The optical spectrum of 3C48 has also been available for some time. Several emission lines were found, but no unequivocal identification with lines of known atoms or ions could be made. Moreover, J. Greenstein of Caltech found that the spectra of some fainter quasars, 3C147, 3C196, and 3C286 (also showing somewhat weaker emission lines), looked quite different from that of 3C48.

M. Schmidt studied the spectrum of the bright object, 3C273. He found four emission lines which formed a simple harmonic pattern with separation and intensity decreasing towards the ultraviolet. This series of lines looks like that of any hydrogen-like atoms. Unfortunately, they correspond to no elements found on earth. A unique interpretation can only be made by assuming a red shift ($\Delta\lambda/\lambda$) of 0.16 and that the emitting element is hydrogen. (A far greater red shift has to be assumed if the emitting element consists of other hydrogen-like atoms.) Indeed, with this interpretation, a red-shifted Hα line (shifted from 6563Å to 7590Å) was found in the infrared by J. B. Oke of Caltech. Similarly, the line spectra of all other quasars can be interpreted as red-shifted emission lines and forbidden lines. In 3C48 the emission line identified corresponds to that of [Mg II] and the forbidden lines to those of [O II], [Ne III], and [Ne IV]. In 3C48 the red shift is 0.37. The corresponding velocity (if the red shift is interpreted as the Doppler shift) is around 0.15 *c* and 0.3 *c* for 3C273 and 3C48, respectively.* Fig. 7 shows the red-shift interpretation of a number of quasars.

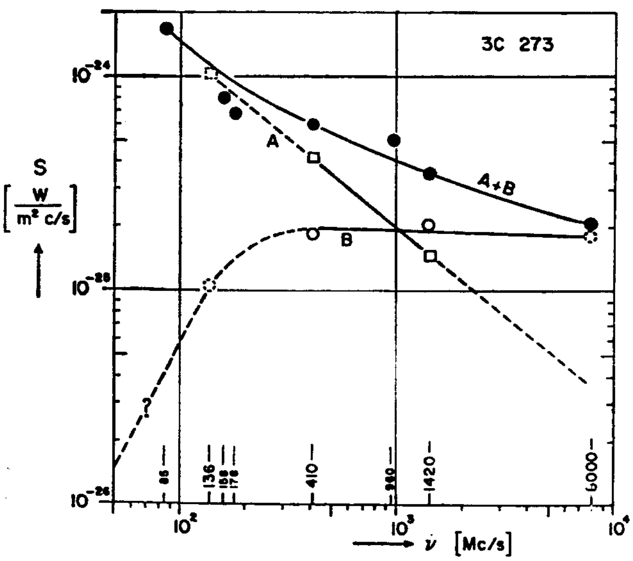


Fig. 6. Radio spectrum of 3C273. Black dots are measurements of both components. Squares give spectrum of component A; the open circles of component B. The line through the open circle shows how one could fit a thermal spectrum to it. But this interpretation seems highly unrealistic. (Courtesy of W. Priester).

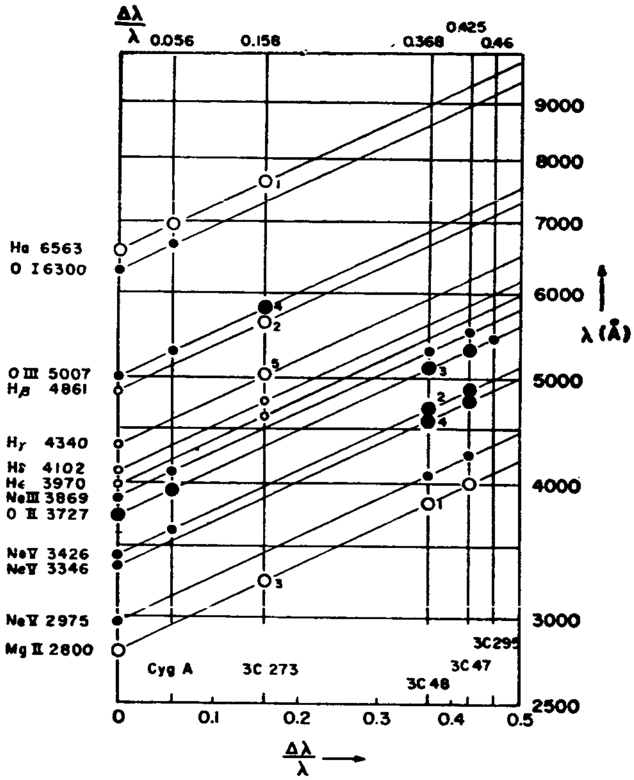


Fig. 7. Schematic spectra of 3C273, 3C48, and 3C47 together with Cygnus A and 3C295. The ordinate is the red shift Δλ/λ. Forbidden lines are represented by black dots. The numbers underneath the dots indicate the relative strength of the lines, number 1 being the strongest line in the spectrum. (Courtesy of W. Priester).

Another feature of quasars is that they show a strong ultraviolet excess even at a red shift of $\Delta\lambda/\lambda = 0.8$. Using filter techniques, A. R. Sandage and M. Ryle have successfully identified a few more quasars (3C9, 3C216, 3C245) from a number of objects showing strong ultraviolet excess.

Could quasars be stars in our galaxy with a high receding velocity? This is extremely unlikely. First, the gravitational field of our galaxy cannot retain

* The Doppler shift is $d\nu/\nu = (-v/c)(1-v^2/c^2)^{-1/2}$, where v is the relative velocity of the source and the observer. For the same velocity most cosmological theories predict a shift $d\nu/\nu$ in between $(-v/c)(1-v^2/c^2)^{-1/2}$ and $-v/c$ (linear).

stars with a velocity $> 10^{-4}\, c$. Second, the proper motion (apparent motion of stars with respect to background stars) would appear large compared with other stars of much smaller velocity.

W. H. Jefferys of Wesleyan University (Connecticut) studied the proper motion of 3C273. Since 3C273 is fairly bright, its image was found among many sky-patrol plates dating back to 1888. Plates from many observatories using different telescopes, accumulated over the past fifty years, were used to determine the proper motion. The inertial system used is the so-called FK3 system. This refers to a group of more than 900 stars catalogued in the *Dritter (Third) Fundamental-Katalog des Berliner Astronomischen Jahrbuchs* (Kopff, 1934) with the highest precision then available.* The measured proper motion of 3C273 is 0.001 ± 0.0025 seconds of arc per year. The standard deviation is from uncertainties associated with the accuracy of the absolute position of stars in the FK3 system. From the value of proper motion and the velocity derived from the differential rotation of our galaxy, the distance of 3C273 is > 65 000 light years, and this puts 3C273 on the border of our galaxy (the size of our galaxy is 10^5 light years). A similar result was also obtained by W. J. Luyten of the University of Minnesota, using more recent plates.

Can the red shift be gravitational in nature? The red shift of light from a self-gravitating body of radius R, mass M, is of the order of $GM/Rc^2 = 10^{-6}(M/\odot)(R/R_\odot)^{-1}$. ($R_\odot$ = solar radius = 7×10^{10} cm). In order to have a red shift as large as 0.1, $(M/\odot)(R/R_\odot)^{-1} \approx 10^5$. For a star of one solar mass and an $R \sim 10^6$ cm, a density of about 10^{15} g/cm^3 would be required. (E. E. Salpeter of Cornell University reviewed the equilibrium configuration of superdense stars. It is not possible for superdense stars of mass $>> \odot$ to exist, nor can the red shift of light from superdense stars exceed 0.3.) The presence of spectral lines implies a surface temperature of the order of 10^4 °K. From the radius of superdense stars, one can estimate the total radiative power, and thus deduce the distance from the observed flux. If 3C273 were a superdense star, its distance would be 0.3 light years and it would be practically inside our solar system! From the intensity of the forbidden lines J. Greenstein further concluded that the distance would be even smaller. Such stars would have been discovered by Kepler through the failure of Kepler's laws!

One may also assume that quasars have bigger masses and bigger radii than superdense stars. For example, one can assume that 3C273 is a star at a distance of 1000 light years. In order to be compatible with the energy output rate, the radius has to be 10^{13} cm. Then, in order to account for the red shift, the mass has to be $10^7\ \odot$! W. A. Fowler pointed out that such stars cannot even burn hydrogen, because they would fall within their gravitational radius before the temperature would be high enough (10^7 °K) to burn hydrogen!

D. Williams of the University of California at Berkeley reported the observation of interstellar absorption lines in 3C273. When radio waves of distant galaxies reach us, part of the energy at the 21-cm wavelength is absorbed by hydrogen in our galaxy. A very weak 21-cm absorption line was found in the radio spectrum of 3C273 with a line shift corresponding to a velocity of 1 km/sec $\pm$ 10km/sec. This effect, however, is very marginal.

Since no other rational interpretation can be given to the red shift, one can only attribute it to the cosmological red shift. Using Hubble's law, the distance of 3C273 is placed at 1.8×10^9 light years. This gives an energy output rate for 3C273 of 10^{46} ergs/sec at optical frequency. Some people will question whether Hubble's law is well established. Hubble's law states that the distance of galaxies to us is linearly related to their red shift:

$$\text{Distance} = \frac{\text{Recession velocity}}{H}$$

The proportionality constant $H(\approx 100\text{km-sec}^{-1}\text{-megaparsec}^{-1})$* is known as Hubble's constant. $H^{-1}c$ is a measure for the dimension of our universe; at a distance $\approx H^{-1}c$ the red shift is total. One often hears that astronomical observations are not accurate enough to distinguish one type of cosmological theory from another, and many have expressed doubts about applying Hubble's law to obtain the distances of unknown objects from their red shift. The answer is that these two problems are somewhat different in nature. Assuming that the local density of galaxies is the same throughout the universe *at a given time* and that the curvature of the universe is everywhere constant, different cosmological theories will predict different galactic densities as a function of the distance (this galactic density is observed from a single space-time point) and the distance is obtained from the red shift by the above equation. The galactic density observed at a single space-time point would be different for different cosmological theories because of the expansion of the universe, and because the expanding rate as a function of the distance is different in different theories. Unfortunately, the various cos-

* Recently, the FK4 Catalogue, containing more than 1200 stars, has been published.

* 1 parsec = 3.25 light years.

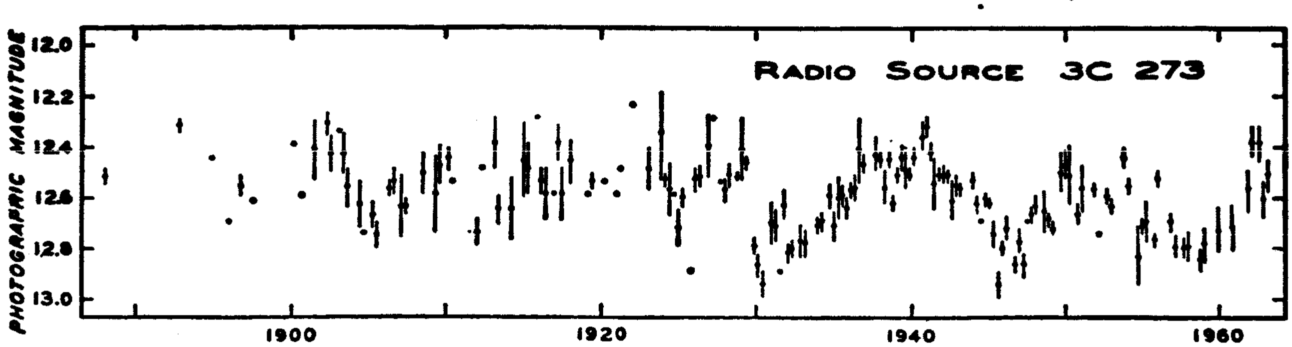


Fig. 8. Light variation curve of 3C273 as analyzed by H. J. Smith and D. Hoffleit from old sky patrol plates. Data represent statistical average over a few days of observations, and standard deviation is as indicated by vertical line segments. (H. J. Smith pointed out that a big light crash of 3C273 occurred towards the end of October 1929. It was a big year for crashes.)

mological theories predict measurable differences in galactic densities only at distances much beyond the reach of the world's most powerful telescope—the 200″ Hale telescope at Mt. Palomar. Hubble's law, however, is established accurately for neighboring galaxies by applying knowledge of the period-luminosity relation of Cepheid variables. (Cepheids are bright variables of luminosity ~ 10^5 $L_\odot$, and their period is related to their luminosity by a simple law. Hence, by observing the period and the apparent brightness of Cepheid variables of other galaxies, one can obtain a distance.) Then the absolute brightness of more distant galaxies is related to the red shift through a complicated statistical analysis eliminating the difference in intrinsic luminosities of individual galaxies. The result is a law that can be trusted to within a factor of 2 in distance estimates. Hence we believe that Hubble's law may be applied to quasars to obtain their distance accurately.

H. J. Smith of McDonald Observatory took a bold look at quasars. Is there light variation in these objects? Sky-patrol plates from Harvard University Observatory are available back to 1888. Although a large number of old plates have aged and become unreliable, some of them are still in fairly good condition. In measuring light variations, one only needs to compare the image of 3C273 with neighboring stars. Smith and D. Hoffleit of Yale found a large light variation with an amplitude up to 50 percent and a quasi-cycle of fifteen years (see Fig. 8). A. R. Sandage observed 3C273, 3C48, and 3C196 more recently with a photoelectric device and found some erratic variations up to a few tenths of a magnitude. From statistical theory, if 3C273 were a galaxy with a nominal number of stars (~ 10^{10}), the expected annual variation would be much less than 10^{-5} of the variation of any star. This limit is obtained by assuming that all stars in the galaxy are variables of the same period. Hence it is not possible that 3C273 and other quasars are compact galaxies. Further, in order that the light from such an object can vary with a time constant ~ 1 year (the shortest variation observed), the physical dimension of 3C273 cannot be much bigger than the time it takes light signals to go across it—namely, one light year.

Having established that quasars are neither local stars nor galaxies, the next thing to do was to study further the details of their spectra. J. Greenstein reported that these lines have been identified with the forbidden lines O^+, Ne^{++}, and Ne^{++++}. Certain atomic excited states decay through higher-order interactions, and their lifetimes are long (~ 1 second). Under ordinary laboratory discharge-tube density ($\gtrsim 10^{15}$ particles/cm^3), collisional de-excitation takes place before atoms in these excited states can decay, and the corresponding lines are ordinarily unobservable in the laboratory (forbidden). The presence of forbidden lines indicates low electron density (< 10^7/cm^3). As the density increases, forbidden lines gradually disappear.

The observed forbidden lines are [O II], [O III], and [Ne III], but [Mg II] is not a forbidden line. Incidentally, a sizable fraction of energy radiated (~20%) is contained in these lines. From their observed relative strength the electron number density N_e may be established. Knowing the distance from the red shift, the absolute intensity of the strength of these lines and hence the total number of atoms emitting them may be determined. The table lists Greenstein's results.

Quasar	*N_e/cm^3*	*Radius (parsec)*	*$M/\odot$ (of emitting parts)*
3C273	10^7	0.6	2×10^5
3C48	10^5	5	2×10^6

If quasars were superdense stars, the differential red shift at different layers would limit the thickness of the emitting layer to that corresponding to the observed width of forbidden lines. This would limit the total number of emitting ions. From this limit and the observed intensity of forbidden lines, Greenstein concluded that quasars would have to be as close as the moon! Such large gravitational perturbations on the solar system could not have escaped the keen eye of Kepler. Hence, from the presence of forbidden lines one can argue indirectly but strongly that the red shift cannot be gravitational.

The lower limit for the masses of 3C273 and 3C48 can be estimated as follows: From the line broadening, we can estimate the kinetic velocity of emitting atoms. It turns out to be 1500 km/sec. In order that these atoms be bound gravitationally at a distance of 0.6 parsec, the center of 3C273 must contain a mass of at least $10^8 \odot$. This is the lower limit for the masses of 3C273 and 3C48.

One can also obtain the mass from energy estimates. To know the total energy radiated, one needs to know the age of quasars. The energy output rate is 3×10^{46} ergs/sec, equivalent to the nuclear energy output from the burning of one solar mass of hydrogen in one day. In 3C273, there is a jet, component *A*, 150 000 light years away from the other component, component *B*. It is most likely that the jet was ejected from 3C273. If one accepts this interpretation, then the age of 3C273 must be at least 150 000 years. This gives a value of 10^{59} ergs for the total energy radiated.

But this is not the whole story about the energy content of quasars. The optical emission can be interpreted as resulting from collisional excitation caused by the thermal motion of ions. From the shape of the radio spectrum (Fig. 6), the radio emission is most likely from synchrotron radiation. Thermal radiation with such strong intensity would require a temperature of the order of 10^9 °K and at this temperature its lifetime against neutrino loss is less than a few days. Relativistic electrons moving in a magnetic field can radiate predominantly in the radio region. To date, we do not know of any way of accelerating high-energy electrons with high efficiency, and it seems consistent with known cases (e.g., the Crab Nebula) that about 1 percent of the energy stored in all high-energy particles may be in the form of high-energy electrons. Also, magnetic fields contain energy. A minimum estimate of the total energy consistent with radio data is at least 10^{60} ergs.

The presence of a magnetic field is further supported by the discovery of polarization in the optical region. One does not expect a very large polarization, because the plane of polarization of electromagnetic waves will be rotated while passing through a plasma; the rotation angle is different for different frequencies (Faraday rotation). Hence, for a given band width, the polarization decreases as electromagnetic waves pass through a plasma. At a wavelength of 4500 angstroms, a polarization of 0.45 ($\pm$ 0.15) percent, based on twelve observations, has been obtained by McDonald. The angle of polarization is defined to $\pm$ 5°. This indicates that there is a small component of synchrotron radiation in the optical region as well.

To summarize the discussion on the observed features of quasars, we conclude that (1) quasars are massive objects with a mass $\gtrsim 10^8 \odot$ which are confined to a space of about one parsec; (2) they are not composed of stars but seem to be coherent masses; (3) their lifetime is at least 10^5 years; (4) they radiate radio waves strongly, but radiate most strongly in the optical region; (5) their surface is composed of very tenuous matter of a particle-number density of the order of $10^7/\mathrm{cm}^3$; and (6) their total energy content is larger than the rest energy of $10^6 \odot$.

Now I shall report some theoretical speculations based mostly on the energy requirement of quasars. All of the 10^{60} ergs of energy ($= 10^6 \odot c^2$) are in the form of magnetic fields and high-energy particles, and a possible energy source is gravitational energy, which can be released in violent events (e.g., collapse); thus all the energy released may be in the form of high-energy particles. The prevalent theory of gravitation is general relativity. General relativity predicts some singularities, one of which, the Schwarzschild singularity, will be discussed briefly below.

Classically, if one is able to accumulate matter indefinitely and statically, the escape velocity at the surface will eventually exceed the light velocity. As an interesting historical sidelight, I remind the reader that in conjunction with the corpuscular theory of light, Laplace demonstrated in 1795 that a body of the dimension of the orbit of the earth around the sun, with a density of that of the earth, would not allow any of its rays to escape. Hence, he concluded that the most luminous object in the universe may not be visible.

The same conclusion holds in relativity theory. In fact, the mass limit calculated according to Newtonian theory is exactly the same as that predicted in general relativity theory! The light emitted at a distance R from a sphere of mass M is red-shifted by the factor $(1 - 2GM/Rc^2)^{-1/2}$ as observed by distant observers; for light emitted at the surface, defined by $R^* = 2GM/c^2$, the red shift is infinite. R^* is called the gravitational radius or the Schwarzschild radius. The time dilatation factor is also $(1 - 2GM/Rc^2)^{-1/2}$. To an outside observer, a body falling towards R^* will never reach it, since in approaching it, the time dilatation factor $(1 - 2GM/Rc^2)^{-1/2}$ diverges and the motion will slow down and eventually stop (time machine!). Signals sent out by the falling body will be more and more red-shifted to very long wavelengths. To a local observer falling towards the center, however, the time of descent is finite. In fact, from the present radius of the sun (7×10^{10} cm), the time of descent towards the center, assuming the sun is within its gravitational radius, is less than one day. For a proton, $R^* = 10^{-33}$ cm; for the sun, $R^* = 2.6 \times 10^5$ cm; and for a massive object $M \sim 10^8\odot$, $R^* \sim 10^{13}$ cm. For a collapsing star in which the pressure can be neglected, J. R. Oppenheimer and H. Snyder, then of the University of California at Berkeley, found in 1939 that the above conclusion was still valid.

Although no light can cross the gravitational radius, the gravitational field and the electrostatic field of the gravitational singularity (those carried by the so-called longitudinal gravitons and photons) can be felt by external observers. Thus, the Schwarzschild singularity can be detected through its gravitational field, but it cannot be seen. Also, because for a comoving observer the Schwarzschild singularity does not seem to exist, many relativists believe it is just a singularity introduced by the particular coordinate one chooses to describe the gravitational field. Various efforts have been made to find a coordinate system free of the Schwarzschild singularity, including a modification of the topology of the space-time continuum, but in all cases, singularities always reappear at other places.

In practice, the Schwarzschild singularity sets an ultimate limit on how far a body can collapse gravitationally. This limit is actually approached in the model proposed by F. Hoyle and W. A. Fowler. In a bold attempt, F. Hoyle analyzed the conditions for the formation of large coherent masses. The difficulties of forming large masses are (1) angular momentum and (2) breaking up of large masses to smaller ones prematurely. The period of rotation is proportional to R^{-2} (R is the dimension of the object), but all other time scales (the free-fall time, the time of transit of hydromagnetic waves across a body) are proportional to $R^{-3/2}$ in the nonrelativistic case. Hence, rotation will prevent matter from condensing further when the speed of rotation at the equator equals the escape velocity. As a comparison, rotation becomes important during the formation of the sun when the radius of the protosun is around 10 to 100 times the present value.

In the relativistic region, all time scales have the same dependence on R. Other physical characteristics of the body (density, mass, magnetic field, and so on) then determine which time scale becomes the

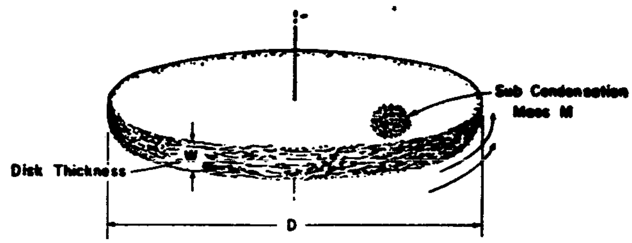


Fig. 9. Flattened disc in Hoyle's theory.

most important one. In order that a large coherent mass may be formed, the gravitational time scale must be the shortest one. A comparison of the gravitational time scale [$\sim (3\pi/32G\rho)^{1/2}$] and the hydromagnetic time scale [$\sim (4\pi\rho)^{1/2}R/H$], where H is the magnetic field, shows that, for a magnetic field of 10^{-6} gauss and a density of 10^{-21} g/cm^3, the gravitational time scale is shorter than that of the hydromagnetic wave when the mass is greater than $10^6\odot$. (As a comparison, the galactic magnetic field is in between 10^{-6} gauss and 10^{-5} gauss, the interstellar matter density is 10^{-24} g/cm^3, and the density of nebulae is 10^{-21} g/cm^3.) From a similar comparison of the rotation time scale ($\sim\omega^{-1}$) with the gravitational time scale, one finds that for $\omega = 10^{-15}$ sec^{-1} (the angular velocity of a galaxy), the condition is $\rho > 5 \times 10^{-24}$ g/cm^3. Thus one need not have a spectacular density in order to overcome the limit imposed by angular momentum.

In this simple argument, one does not consider the transfer of angular momentum from one part of the body to the other. If considerable amounts of angular momentum are transferred, the previous argument is not valid. It is not known whether angular momentum may be transmitted in large quantities. Optimistically, one hopes the inner part can fall a great way before transfer of angular momentum becomes important.

Thus, conceivably, a large mass ($\gtrsim 10^6\odot$) can condense to a density of around 10^{-16} g/cm^3. At this density, due to rotation, the body becomes appreciably flattened (see Fig. 9). Let the thickness of the disc be W, the diameter be D. Now the time scale for the vertical direction is determined by W and this gravitational time scale is much larger than the hydromagnetic time scale. Fragmentation can now take place in the outer part. The mass m in each fragmented blob is given by $m/M \sim (W/D)^2$; for $W/D = 10^{-2}$ and $M = 10^6\odot$, we have $m = 10^2\ \odot$.

The temperature of the gas can be calculated by applying the virial theorem (which equates the thermal energy of a self-gravitating sphere to its self-gravitational energy). The calculated value for this case is around 10^4 °K, somewhat below the ionization temperature of hydrogen at the corresponding density. Further contraction (now taking place individually in smaller blobs) will raise the temperature, and hence ionize the gas. The ionization of hydrogen requires an energy of about 10^{13} ergs/g and the thermal (and gravitational) energy is about 10^{12} ergs/g at 10^4 °K. The gravitational energy is proportional to R^{-1}. To obtain an energy of 10^{13} ergs/g, a contraction by a factor of ten, or an increase in density by a factor of 10^3 is needed. The density suddenly increases from 10^{-16} g/cm^3 to 10^{-13} g/cm^3.

The gas cloud becomes opaque to radiation only until $\rho \sim 10^{-11}$g/cm^3. During the contraction phase, energy has to be supplied to the radiation field as well. Hence the contraction cannot stop until a density of 10^{-11} g/cm^3 is reached. As I have mentioned earlier, stars of masses $\gtrsim 10^2\odot$ are not stable against pulsation. A check on the thermodynamic mechanical properties of a 100 $\odot$ star shows that it is only marginally in stable equilibrium. Now a rapid contraction takes place almost like a collapse, suddenly raising the density from 10^{-16} g/cm^3 to 10^{-11} g/cm^3 in a time comparable to the gravitational free-fall time. Will the collapse stop? In a star of a few solar masses, we are quite sure that the collapse will stop before nuclear energy generation runs wild. The kinetic energy associated with the collapse will be damped out in the subsequent oscillations. In a 10^2 $\odot$ star, the collapse will probably overshoot, and the accompanied oscillation will have very large amplitude.

The most efficient damping mechanism is the electron-pair annihilation process of neutrino production. But this is important only when $T > 10^9$ °K; at lower temperature, there is no damping. Since the temperature fluctuation of the star is very large, nuclear reactions (hydrogen burning) will proceed in a somewhat erratic manner. An estimate of the actual time scale for nuclear burning is difficult; but, in order to fit those sporadic light variations in 3C273, the time scale for nuclear burning should be around one year. This rate also fits the observed energy flux (3×10^{46} ergs/sec).

S. A. Colgate of Lawrence Radiation Laboratory and A. G. W. Cameron of Goddard Institute for Space Studies pointed out, however, that F. Hoyle's mechanism does not provide enough high-energy particles for radio emission. Shock waves generated by supernovae, traveling in the very tenuous matter in which these stars are embedded, will accelerate particles to relativistic velocities. A considerable amount of gravitational energy will be released during supernova collapse. Moreover, shock waves will generate hydromagnetic waves throughout the medium, which may explain the long-term light variations (15 years) of 3C273.

Remnants of these massive stars may be in the form of neutron stars or a Schwarzschild singularity, either of which may accelerate particles to relativistic speeds. This may be the mechanism that produced a jet in M87, a galaxy. The idea of acceleration was advanced by Ya. B. Zel'dovich of the USSR.

Another alternative suggested by Hoyle is that the inner region of the big body can collapse gravitationally to extreme density; rotation can either be crushed by gravitational force or dissipated by radiating gravitational waves, assuming a noncylindrical shape was achieved through fission. F. Dyson of the Institute for Advanced Study remarked that the difficulty associated with a gravitational-collapse theory is that it would be over in one day (the local time it takes for a test particle to cross the Schwarzschild singularity of $10^2\odot$). How can a state of collapse be maintained for over 10^6 years, which would be required in quasars?

T. Gold of Cornell pointed out that in supernova explosions the light output increases rapidly but declines slowly, and this is in contradiction to what is observed in quasars (see Fig. 8).

Hoyle summarized his talk with a diagram which is reproduced here as Fig. 10.

W. A. Fowler then discussed a similar mechanism for massive objects. As condensation takes place, the inner part begins to rotate rapidly, and fission can take place. When the inner part bifurcates into a nonsymmetrical form, gravitational radiation will take place, radiating away an appreciable amount of rotational energy (which is comparable to the total rest energy). This raises the potential energy outside, and part of the matter will have a positive binding energy. Mass will be ejected. The difficulty here, as pointed out by a number of others, is that one cannot avoid a coupling between inside and outside if fast nonsymmetrical rotation takes place.

T. Gold presented the idea that if stars escaping from star clusters can carry away enough angular momentum, star clusters can collapse, and collisions between stars will occur more frequently. Energy released in such collision processes is fairly large, and certain radio phenomena can be explained.

A number of other topics not related to massive objects, but relevant to gravitational collapse or to galactic structure were also discussed.

E. M. Burbidge reviewed several proposed mechanisms for strong radio sources. Originally, a radio source in Cygnus was identified with a pair of galaxies appearing to be in collision. R. Minkowski of the University of California at Berkeley postulated

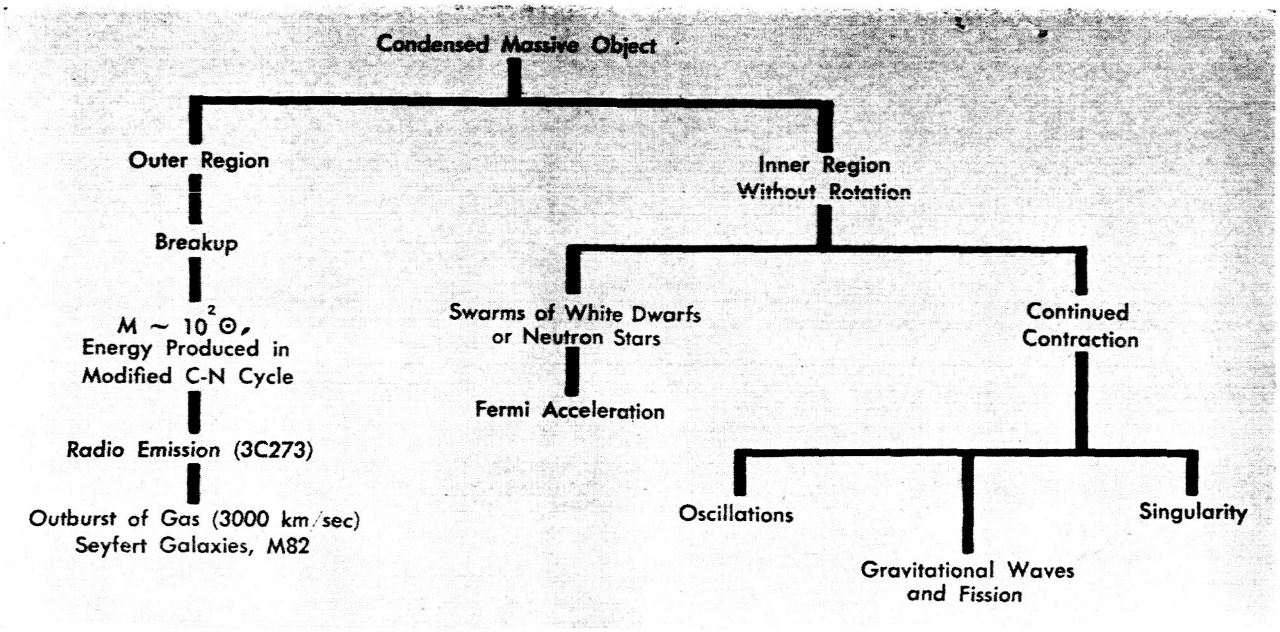


Fig. 10. Chart summarizing possible mechanisms of gravitational collapse proposed by F. Hoyle.

that collision between normal galaxies could generate high-energy particles responsible for radio emission, but this idea was later rejected because the energy thus released would be far too small. Also, the known number of radio sources is much greater than would be expected from the frequency of galactic collisions for most optically identified sources not associated with clusters of galaxies. G. R. Burbidge of the University of California at La Jolla and F. Hoyle proposed that collisions between galaxies and anti-galaxies (composed of anti-matter) might give enough energy. However, there are many inconsistencies in this proposal. For example, why should matter and anti-matter be separated until the right moment to annihilate? Another mechanism is the emission of radio waves through the interaction of a turbulent magnetic field with gases. One can perhaps explain the radio emission from M82 by this mechanism, but in an elliptical galaxy, there is practically no gas! The existence of large scale, strong magnetic fields in elliptical galaxies is also unlikely.

If one accepts supernova remnants as the only radio emitters in a galaxy, one needs a total number of 10^{8} supernovae spreading over 10^{9} years. I. Shklowsky of the USSR suggested that during the early stages of galactic evolution, rapid star formation can take place, and supernova activities may be stronger than at present. A. G. W. Cameron modified Shklowsky's idea, proposing that in regions rich in gas and low in magnetic field, massive stars can condense simultaneously. After going through their normal evolutionary sequence, they become supernovae—all in around 10^{6} years. Remnants of these supernovae can account for the radio emission. The difficulty is the same as in the proposal of G. R. Burbidge and F. Hoyle: in elliptical radio galaxies there appears to be very little gas.

G. R. Burbidge postulated that in the center of a galaxy, if the separation between presupernova stars is around a few light days, the supernova explosion of one of them may trigger the rest of them to become supernovae. In order that his mechanism may work, a stellar density of 10^{7} stars/cubic parsec is needed. Such a high density may exist and escape detection. However, one does not know of any trigger mechanism.

H.-Y. Chiu of Goddard Institute for Space Studies reported on a study of the evolution of presupernova stars in which it was found that a very dense core will develop before a star undergoes collapse. Almost all the energy released during collapse will be dissipated in the form of neutrinos, and the dense core will become neutron matter.

E. E. Salpeter reviewed the equilibrium configuration of neutron stars. At a density greater than 10^{12} g/cm^{3}, matter is composed predominantly of neutrons, and at an even higher density ($> 10^{16}$ g/cm^{3}) hyperons may exist. These neutrons cannot decay because all electron states are filled up. There exists a mass limit for neutron stars, and no static equilibrium configuration is possible if the mass exceeds this limit. This limit for a perfect Fermi gas is $0.76\odot$ (Oppenheimer-Volkoff mass limit). If real gases are considered, the limit varies somewhat, but in no case does it exceed $3\odot$.

H. Bondi of King's College, London (reported by E. E. Salpeter), derived a rigorous upper limit ($\Delta\lambda/\lambda < 0.615$) for the red shift of light emitted from the surface of neutron stars. A more realistic limit is found to be around 0.3, which incidentally also excludes the possibility that the large red shift (> 0.3) of some quasars is a gravitational red shift. In principle, this is the upper limit of the red shift for light emitted from any self-gravitating body.

J. A. Wheeler of Princeton discussed another kind of gravitational singularity. He assumed that one can accumulate matter *statically* until at the center, the time metric g_{00} vanishes (this corresponds to a classical situation in which the gravitational potential *at the center* of the body is equal to its rest energy). Any matter dropped through a hole to the center will give away energy equivalent to its rest energy and thus the total gravitational mass (as observed by external observers through its gravitating effect) cannot increase. Such a singularity acts as a gravitational machine, converting all matter into energy. Since the number of nucleons is conserved, Wheeler postulated the existence of a class of new massless bosons, the δ ray, which carries the nucleon number. One of the chairmen remarked that δ rays, if they exist, may be used to transport ponderable matter at the speed of light.

However, it is not known if one can really accumulate matter statically until this kind of gravitational singularity comes into existence. All neutron-star models studied so far indicate that a dynamical collapse will take place when the mass exceeds the critical mass limit (the mass limit was reviewed by Salpeter).

A spirited discussion then took place, reemphasizing some of the points discussed during the meeting. E. L. Schucking of the Southwest Center for Advanced Studies pointed out that other discussions relevant to massive objects, cosmic rays, and cosmic x and γ rays had been omitted from the discussion. P. Bergmann of Yeshiva University remarked that in the past general relativistic effects had been observed only in the weak field limit. Now new developments of astrophysics have made relativity a more physical theory. He expressed hope that a quantized version of relativity theory may play an important part in understanding massive objects. R. Minkowski expressed satisfaction that within the past ten years the technique of optically identifying radio sources had made great progress. On the other hand, a theoretical understanding of the structure of large masses is lacking. In one context, J. R. Oppenheimer, who pioneered the study of neutron stars and gravitational collapse, remarked that the present situation in interpreting quasars resembled that of quantum electrodynamics eighteen years ago, when all one had was confusion and lots of data. If the meeting taught us anything, it has taught us that those two dark clouds in the otherwise clear sky of physics (Kelvin, at the turn of the last century, was referring to natural radioactivity and x rays) are still there. But they are now to be found at the very edge of our universe.

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